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ABSTRACT

This paper presents a three-phase model of how formative evaluation research can inform the design of educational computer software products. Used as an illustrative case is a program of formative research conducted on "The Talking Clock," a computer assisted instructional software product designed to help children in kindergarten through second grade learn about clocks and time. This paper discusses how the formative evaluation addressed design and interaction issues including students' prior learning, formulation of learning activities, design of icons and the functioning of graphic objects, choice of mouse vs. touch screen as an input device, and classroom usability. Also addressed were such issues of classroom management as how well teachers could track students' progress, monitor their problem solving with the software, and assess their learning. (8 references) (DB)

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Formative Research in the Development of Mathematics Software for Young Children

Cynthia A. Char

Report No. 90-1

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Formative Research in the Development of Mathematics Software for Young Children

Cynthia A. Char

This paper presents a three-phase model of how formative research can inform the design of educational software products. Used as an illustrative case is a program of formative research conducted on *The Talking Clock*, a software product designed to help children in kindergarten through second grade learn about clocks and time. This paper discusses how formative research addressed key design and user interface issues, including initial formulation of learning activities, design of icons and the functioning of graphic objects, choice of input device (mouse vs. touch screen), and classroom usability.

The educational potential of computer software and interactive video is tantalizingly promising. With their high quality graphic, audio, and text capabilities, large storage capacity, and immediate responsiveness to users' interests and ideas, these media offer an unprecedentedly rich resource for enhancing the learning of children and adults.

Accompanying all these intriguing possibilities, however, is an equally sizable challenge to software designers and producers to figure out how best to harness all that "media horsepower" creatively and wisely. Given the technology's short history, few good models or examples of interactive learning products exist. Furthermore, the youthfulness of the field compels all in the software industry to attempt to break new ground regarding what is possible and educationally valuable.

The standards of many serious software developers are quite high. These developers

strive to make the images, sounds, and text in their programs of sufficiently high quality to compete with users' expectations as developed through television, home stereo systems, and beautifully illustrated books. Moreover, such developers believe that the interface should make users' interaction with the software transparent, natural, and fluid, much like a satisfying exchange with a friend or teacher, or the experience of working with a specially handcrafted tool.

Furthermore, materials are not used in a vacuum, but rather in particular settings by specific individuals. As it would be folly to design an educational lesson without some in-depth knowledge of the age and characteristics of the student, as well as the features of the intended classroom environment, so is it ill advised to design educational software without some empirical "checks and balances," achievable by soliciting feedback from potential users of the materials.

Despite the formidable challenges of designing powerful interactive materials, rarely is software under development tested by the targeted users. More often, software designers rely on their own creative hunches, intuitive sense, or image of the user. Alternatively, they may informally solicit reactions from adult colleagues, or perhaps their own or others' children, in the case of a product intended for children.

If any more systematic testing is used, it is most likely in the form of "beta tests" or field tests conducted by an outside research group to evaluate products that are already in their finished, or close-to-finished, state. Research at this point in the development process, however, can do little more than offer a stamp of approval. Design improvements based on user feedback are likely to be minimal at best, given that considerable time and resources have already been devoted to the product, the program code already exists, and a limited budget and pressing production deadlines remain.

There is, however, growing recognition in the educational software and interactive video fields of the utility and value of formative research *throughout* the development process (e.g., Char, 1987; Quinsaat, 1989; Revelle, 1989; Rheingold, 1990). In contrast to basic research in cognitive psychology, which is driven by theoretically-based learning hypotheses and statistical criteria of research design and sample size, formative research agendas are defined by particular design issues and characteristics of the target audience. The issues addressed by the research can be as varied as the specific characteristics of the product, and the issues may continue to shift as the design process evolves (e.g., Hoelscher, 1989; Rockman, 1990; Schauble, 1990; Wilson & Tally, 1990).

This paper presents a model of formative research that was used by the Elementary Mathematics Project at Education Development Center (EDC) in the creation of mathematics software designed for young children. The sections that follow briefly describe the software, the project structure, and the formative research process, and then, using one of the software products as an illustrative case, outline a program of research consisting of three major phases.

The Project Materials

With funding from IBM, the Elementary Mathematics Project explored the use of "on-screen manipulatives"—computer graphic objects that serve as a new form of math manipulative for young children. One of the products developed is a set of software programs called *Exploring Measurement, Time, and Money—Level I.* The software is designed to enhance the early mathematics learning of children in kindergarten through second grade. For each of the three domains—measurement, time, and money—the software provides an integrated set of structured activities and open-ended graphic tools for children's mathematical exploration, problem solving, and expression.

For example, the *Talking Clock* software, designed to enhance children's learning of time, consists of five different programs. *Explore* resembles an electronic, talking feltboard. With this program, children can set the hands of a clock to whatever position they desire. Then, by clicking on a mouth icon, they can hear that time spoken, via digitized speech. The remaining four programs (*Match the Time, Set the Time, Set: Before and After,* and *Make a Story,*) offer more structured activities that address reading a clock, concepts of before and after, and logically sequencing a series of time settings to tell a story.

The software, with colored graphics and digitized speech, is designed for the 256K IBM PS/2. The clock software will serve as the primary software case study for this paper.

Project Structure and Formative Research Process

The project staff was organized into interdisciplinary design teams consisting of curriculum experts and teachers, software designers, graphic artists, programmers, and researchers. From the time the project began, researchers met regularly with students in the target age group to solicit their reactions to the evolving materials. This process ensured that the design team received early and ongoing feedback on the program's concept, design, and user interface, allowing them to maximize its educational value, appeal, and usability.

One of the major challenges in conducting formative research is to be sure that the issues are researched, the materials are tested, and the information is processed and delivered quickly and efficiently so as to keep up with the rapid clip of most software development efforts. Throughout most of the project's one-year development schedule, researchers met almost weekly with students or teachers. The reporting back of results to other members of the design team usually occurred within twenty-four hours of completing the round of testing, first verbally, and then within two or three days in the form of a written research memo. As with similar formative research efforts, the size of the sample that tested any one version of the software was typically small (e.g., twelve to twenty students), since the software was changing rapidly. New versions of the software arose from the completion of additional code or graphics, and from modifications based upon user feedback from each testing session.

Testing with users began shortly after the first design meetings before any code was written, in order to inform the formulation of the product concept and initial definition of the product's software activities. The last round of user testing was completed just prior to the completion of the code, when the software was sent off to be tested for bugs, final code completed, and the product shipped. The yearlong formative research process consisted of three major phases, as described below.

Phases of Formative Research

Tapping Users' Prior Knowledge and Experience

The first phase of formative research investigates the prior knowledge and experience which users bring to their interaction with the software. This research is most useful during the initial stages of developing the product concept. Essential information that can be discovered during this phase includes children's familiarity with, current understanding of, and possible misconceptions concerning the content to be addressed, as well as the strategies and background knowledge children call upon to solve sample problems. Finally, such initial research can determine whether the planned activities are appropriate for the target audience, in this case children in kindergarten through second grade.

We used two strategies to gather this baseline of background information. The first involved an analysis of the relevant sections of existing textbooks. For example, for the *Talking Clock* software we analyzed the time-related problems in three major textbook series. Our analysis considered such dimensions as curriculum goals (telling time, understanding duration, sequencing events); levels of problem (e.g., hour vs. half hour); nature of presentation (e.g., relative emphasis upon analog vs. digital clocks, focus on numeric symbols); and the nature of the user response (e.g., time-telling recognition tasks, production tasks such as drawing clock hands to indicate a time).

The second baseline data-gathering strategy involved sessions with first- and second-grade children. Through clinical interviews and observations, we noted how children solved problems using paper and other materials that offered an experience similar to the one we intended to create with our software. We have found that meeting with pairs of children, rather than with individuals, often works particularly well in formative research studies. Children feel more at ease in the session since they have company, and they express more of the reasoning, reactions, and decision making elicited by the software as they interact with their partners.

Meeting with pairs of children, we researched

their awareness of clocks, the role that clocks play in their lives, and their current understanding of telling time. We learned that the children (1) were well aware of the different kinds of analog and digital clocks they had at home; (2) had difficulty reading analog clocks, beyond the hour setting, and were more likely to rely on digital clocks for their personal use; and (3) had a general sense of how times were associated with different events in their day, such as when they went to school in the morning, when they ate dinner, or when a certain television show came on.

Furthermore, by observing how children arrived at solutions to worksheet problems and worked with paper clocks with movable hands, we discovered that many possessed a range of interesting, but incorrect, notions about half-hour settings. For instance, some children interpreted "-thirty" or "half past" to mean either that

- the big hand points to the 3 (since 3 stands for 30) or that
- the little hand points to the number that is half the number of the hour indicated (e.g., 8:30 means you put the little hand on the 4, since 4 is half of 8).

One inventive child knew that showing the half hour somehow involved counting by fives, but was certain that the counting by fives should begin from the hour numeral. Thus, to represent 8:30, this child would count by fives from the 8 and end with the minute hand pointing at the 2. We also learned that a common error across all time settings was reversing the minute and hour hands.

Obtaining this kind of information about potential users allowed us to anticipate common types of misconceptions that children are likely to have and incorrect strategies they are likely to use. The information was valuable in our construction of appropriate problem sets, wording of help prompts, and design of corrective feedback. For example, our studies provided evidence that children are able to *recognize* time settings correctly before they are able to *produce* those settings (i.e., indicate where the clock hands should go). This result suggested the importance of including as one of the early activities in the software a matching activity that would help lay some of the foundation needed before children could successfully tackle a clock-setting activity. Having greater understanding of children's likely misconceptions also informed the types of incorrect options we included in the problems.

User Interface

A second phase of formative research involves user interface issues, usually addressed once the initial product concept is well defined and the form of the software has begun to take shape. At this point, the graphic artist has rough sketches of icons and the general layout of the screens. The user interface research addresses the ways in which children understand and interpret the software presentation and screen design, and the extent to which they're able to control the software program successfully using the input device.

In our project, this research addressed a broad category of design concerns, including choice of input device (e.g., mouse vs. touch screen); design of screen layout and icons; use of computerized speech; and further refinement of help prompts, problem sets, and corrective feedback.

Based on user feedback, software prototypes are revised. This research/design phase is the most iterative; during this phase the software prototype evolves and is tested a number of times in its successive versions. For example, we tested four different versions of the *Talking Clock* software within a three-week period. Each successive version of the software had been further developed and had incorporated some findings from the previous testing session.

As in the earlier phase of gathering background information, the user interface research involved clinical observations and interviews. Again, we worked closely with pairs of children, talking with them and observing how they worked with a variety of materials that simulated aspects of the software product. At this stage, however, these materials were no longer solely paper and pencil or real objects (e.g., coins for testing our money software and rulers for testing our measurement software); rather, the primary testing materials included software storyboards (i.e.,

"slide show" sequences of static software screens) and early versions of working, interactive software.

Our software needed to allow children to manipulate graphic objects, setting the hands of the clock, for example, or dragging coins and numbers onto the screen to create and solve money problems. As a result, decisions surrounding the optimal input device for young children and the ease with which it allowed easy manipulation of graphic objects were a central design concern. Thus, one of the first studies we conducted was designed to determine whether the mouse or the touch screen was better suited for our software.

At first glance, it might appear that the touch screen, with its direct correlation between user gesture and on-screen response, would be the preferable input device for young children. However, we quickly discovered that the touch screen posed considerable hurdles for child users. For one thing, it would have to be calibrated to account for the user's vantage point and angle of gesture. Given the complications posed by the different vantage points of two people, the touch screen was not well suited for use by more than one person at a time, yet our software was designed for use by children working in pairs.

Furthermore, we discovered that children spontaneously touch the screen in the process of counting objects and referring to items that appear on it. Thus, it was likely that a child would point to the screen not so much to indicate her selection at some decision point, but to help with the process of figuring out the problem. She might point to each numeral on the clock as she counted by fives, for instance, to figure out what 2:20 might be. Such "problem-solving gestures" would mistakenly be read by the computer as inputs and would trigger a response.

For these reasons, we decided that the mouse was the preferable input device. Over the course of our formative studies with over 800 children who worked with one of our measurement, time, or money software programs, we found that young children can learn to handle the mouse surprisingly quickly, following a brief introduction and modeling by an adult or experienced peer. We were also able to anticipate the kinds of problems children are likely to encounter during their initial experiences with the mouse, such as turning the mouse around the wrong way, not knowing what to do when it reaches the end of the tabletop, or lifting the mouse in the air to move the cursor up. We were therefore able to specify the types of directions, including suggestions for modeling correct use of the mouse, that should be included in the teacher guides accompanying our software.

An input device, of course, is inextricably related to the ways in which software is designed, and it only succeeds to the extent that the program supports its strengths and acknowledges its limitations. Thus, once we had decided on mouse input, a major focus of our interface research was the refinement of the interface between mouse input and graphic object manipulation. For example, with the clock software, we needed to decide how children would set the hands of the clock. In the initial design of the software, a child clicked on the mouse to start the clock running and then clicked on the mouse again to stop the clock when the hands were in the desired location. Movement of the two hands of the clock was interconnected; advancing the time from 2:00 to 3:00, for example, meant that the minute hand moved all the way around the clock. In this way, the clock hands acted in the same manner as those on a real clock, simulating the passage of time.

In testing out this design, however, it became apparent that it had serious shortcomings. First, we learned that children tend to focus on the final state of the clock hands, not on any of the intermediate positions. So, if they wished to change the time from 2:00 to 3:00, they simply wanted to move the hour hand to 3, leaving the minute hand on the 12, since it was already in the correct position. Thus, the children found the movement of the minute hand around the clock to advance the hour hand extraneous, confusing, or even distressing.

Second, the initial design required two different pacing levels. On the one hand, the clock hands needed to move quickly enough so that it was not tedious to advance the clock over the span of several hours. On the other hand, the software needed to give children sufficient control

to stop the hands once they were in the desired position. However, determining "How slow should slow be?" was difficult, and the answer varied for different children. Some children were able to anticipate when the hands would be in the desired position so they could time their mouse click to stop the hands in the position they wanted. In contrast, others only seemed to recognize the correct setting once the hands were in that location. By the time they clicked on the mouse to stop, the hands had already advanced to another, incorrect, setting.

For these reasons, we decided to adopt an interface that allowed children to control the hour and minute hands directly, by clicking on a different colored clock hand icon to indicate which clock hand they wished to move. The children could also indicate whether they wished to advance the hands clockwise or counterclockwise. The interconnectedness of the clock hands was apparent mainly in relation to the movement of the minute hand. (For example, if a child advanced the clock from 3:30 to 4:00 in five-minute increments by moving the minute hand, the hour hand also slowly moved to the numeral 4.)

Field Tests for General Usability

Finally, a third phase of formative research concerns the general usability of the software by children and teachers in classroom settings. This type of research usually takes the form of field tests, conducted once the product concept and design are well defined and a good, working version of the software has already been improved and fine-tuned through earlier rounds of user testing.

In contrast to the typical "one-shot" field test in which researchers may be seeing users interact with software for the first time, our third formative research phase focused less on how individuals or pairs of children worked with the software (since we had already caught most of the problematic interface and screen design features in earlier research) and more upon the unit of the classroom. Through classroom observations and teacher interviews, we examined how materials were used in a classroom of twenty to thirty students, and studied the role of the teacher in guiding children through the flow of lessons and in interpreting and shaping children's work with the materials.

Design issues addressed in this phase of our research on *Exploring Measurement, Time, and Money* included how well the software and accompanying print materials were supporting the multiple modes of instruction required in the classroom (i.e., large group demonstrations and discussion, small group work, independent work) and how well the software reinforced, complemented, and extended learning experiences with manipulatives and print. Also addressed were issues of classroom management, such as how well the teachers could track students' progress through the materials, monitor students' problem solving with the software, and assess students' learning.

Conclusion

In summary, these three phases of formative research—studies on children's prior knowledge and experience, user interface research, and field tests for classroom usability—constitute a comprehensive approach to obtaining user feedback at all stages of software development. Collectively, they can provide educational software designers with valuable information about a range of software features, including input devices, design of icons and screen layout, use of computerized speech for help prompts and corrective feedback, and ease with which the software can be incorporated into the day-to-day workings of a classroom. Working together, formative researchers and software designers can hope to meet the formidable challenge of designing high quality educational software for children that is comprehensible, engaging, and successful in meeting its pedagogical objectives.

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